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Synergistic Interactions of Wear, Corrosion and Fatigue: Degradation Mechanisms and Protection Strategies: A Comprehensive Review

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Abstract: When abrasive sediment and aggressive water chemistry combine with the repetitive cyclic loading of a hydraulic gate, these forces create the perfect storm for premature failure of the hydraulic gate due to the synergistic effects of abrasion, erosion, fatigue, fretting, pitting and crevice corrosion as well as stress-corrosion cracking. This review will detail the various degradation modes individually and in combination, including abrasive-erosive wear, fatigue fretting and pitting/crevice corrosion that is enhanced by stress corrosion cracking. Additionally, this review will compare conventional protective measures (paint, corrosion allowance and cathodic protection) with emerging thermal spray coatings. Special emphasis will be placed on high velocity oxy fuel (HVOF) cermet coatings with NiCrBSi matrices with Wc, CrC – NiCr or Al_2O_3 reinforcement, achieving greater than 70 HRC hardness, less than 1% porosity, and a metallurgically bonded interface between the substrate (mild steel) and the HVOF coating, resulting in an increased service life from three to five times longer than conventional coatings during slurry erosion-corrosion testing and salt spray testing. In addition to providing microstructural, mechanical and electrochemical test results for optimizing the carbide content within the HVOF cermet coating as well as post fuse treatment techniques to inhibit the formation of cracks and the subsequent spalling of oxides; gaps are identified including: lack of life prediction models that include actual field sediment spectra, eco-friendly alternative materials for hard coatings, and data driven selection of coatings based upon field conditions. Finally, the authors conclude that using HVOF cermet coatings, along with real-time corrosion monitoring and "green" feedstock powders, will provide the best route to developing long-lasting, low-maintenance hydraulic gate infrastructure to meet future water security challenges.

Introduction

Background and Significance of Hydraulic Gates

The hydraulic gates are vital components of hydraulic structures for controlling the levels, pressures and flows in reservoirs, dams, barrages, canals, and power stations. The reliability of these gates is essential for flood protection, water supply, transportation and hydropower generation. Conventionally, these gates are made from weldable mild steel (for example, IS 2062), which have to endure impacts from floating objects, sediment-laden flow with high velocity, cyclic loading due to opening/closing, and static heads. As such, these gates undergo considerable mechanical and chemical degradation, causing loss of sealability, deformation and resulting in expensive emergency shut-downs. A study indicates that failure of a single spillway gate may result in costs of over $10 million for repairs and lost revenues during unplanned outage periods. Therefore, increasing the service life of gates is important for water security and as an economically viable option for maintenance.

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Role of Surface Engineering in Extending Service Life

Surface engineering is considered one of the best options to mitigate both erosion and corrosion when compared to replacing alloys and allowing for corrosion by design. In addition to providing protection against wear and corrosion, surface engineering provides many other benefits. Coatings applied to surfaces provide a protective layer between the base metal and aggressive media, preventing contact between them. The various types of surface coatings include sacrificial, barrier, and passivation coatings that protect the base metal from abrasives, oxygen, and corrosive ions. Thermal spraying processes, specifically High Velocity Oxy-Fuel (HVOF) enable the application of thicker (200–800 µm) coatings with lower porosities (less than 1%) and higher hardness values (over 65 HRC) as well as higher bond strengths (greater than 70 MPa) than previously possible using traditional coating methods. The post spray fusion of the NiCrBSi-based coatings enhances the interfacial strength of the coated substrates by eliminating crack propagation along the thickness of the coatings and galvanic attack at the interface. Thus, the surface engineering of the hydraulic gates transfers the degradation region from the structural steel to an engineered and replaceable surface coating, allowing longer time between inspections and enabling the use of predictive maintenance techniques.

Objectives and Scope of the Review

The objective of this study is to synthesize the most recent knowledge on the failure mechanisms unique to hydraulic gates and assess the conventional and innovative protective treatments for the surfaces of hydraulic gates. The objectives of the study are:

a) delineate individual and synergistic wear/corrosion modes;
b) benchmark paints, metallic platings and cathodic systems against thermal-sprayed coatings;
c) highlight microstructural design, mechanical performance and field durability of HVOF NiCrBSi-WC/CrC–NiCr/Al_2O_3 composites; and
d) identify research gaps life-prediction models, eco-friendly powders, and smart monitoring that must be addressed to realize next-generation, sustainable hydraulic-gate infrastructure.

Overview of Hydraulic Gate Systems

Types and Functions

Hydraulic gates can be manufactured in geometrical shapes suited to the operation of hydraulic systems.

a) **Radial (Tainter) gates** revolve around a trunnion within a pier; the hydrostatic pressure is transmitted through the pivot point thus reducing the weight required to lift the gate, hence they are the preferred type of gate for large spillways (USACE, 2014).
b) **Vertical-lift (Slide) gates** slide vertically in the slot in which they reside, provide a seal when operated with low to moderate head values, and are commonly used in irrigation outlets; versions of these gates equipped with rollers to move the gate will result in less friction (Liu et al., 2021).
c) **Canal gates** (flaps, butterfly, sectors) allow for the control of small quantities of water and are required to quickly respond to automatic level controls (Bureau of Reclamation, 2016).

Each of the different types of gates produces its own unique flow pattern: Radial gates produce a high velocity jet down the curved lip of the skin plate as it accelerates the fluid flowing past the gate, and then sweep the face of the gate downstream; vertical lift gates create localized wear "hot spots" on the lower leading edge of the gate and the guides by concentrating the flow onto those areas (Rajahram et al., 2009).

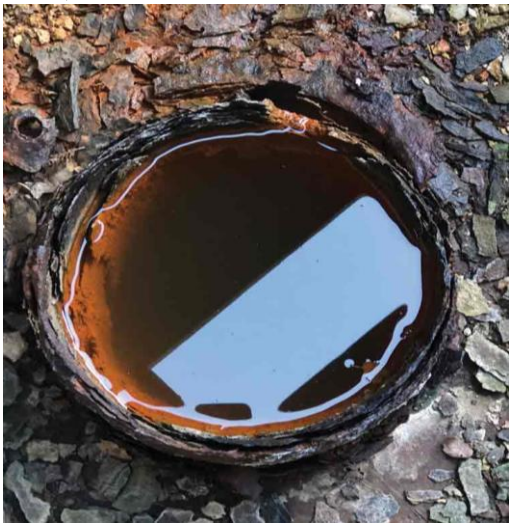

Figure 1. Casing pipe for a well system that has corroded at the surface: illustrative of the uniform and galvanic attack that also occurs on gate components exposed to groundwater.

Figure 2. Column pipe that is heavily corroded: comparable to the crevice and oxygen-cell corrosion found beneath gate seals and backing bars.

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Common Materials Used

The choice of materials depends on the cost, their ability to be welded, and how well they will perform under the stresses of a structure.

a) **IS 2062 grade B mild steel** having a yield strength of 250 MPa and is by far the most commonly used structural plate (BIS, 2011).
b) **Cast steel** (or Spheroidal Graphite SG iron) can be used as rollers, trunnions and seal housing components.
c) **Stainless steels** (AISI 304L, 316L) are reserved for all areas that have a risk of corrosion, such as seal seat, stem, and fastener applications, where there is a need to minimize the occurrence of pitting or galling (Cunat, 2001).

Figure 3. A pump component that is showing heavy erosion: representative of the erosion–corrosion damage observed on gate skin plates and leading edges subjected to high-velocity sediment-laden flow.

As a result of the use of dissimilar metal pairs (i.e., stainless/ carbon) in these applications, galvanic cells will form when submerged (Jones, 1996). These welding consumables, typically E250B or low hydrogen, are usually used to match the base metals being welded; however, due to the thermal effects of welding, the HAZ will soften, and if the weld area remains exposed to chlorides, it may experience stress-corrosion cracking (Sridhar et al., 2020).

Operating Environments and Degradation Challenges

Gates operate intermittently, often standing idle for months before rapid opening under flood draw-down. During monsoon or snow-melt, flow velocities exceed 10 m s^{-1} and suspended-sediment concentrations can surpass 5 kg m^{-3} (Koch et al., 2002). Cyclic wet–dry and oxygen-rich splash zones accelerate uniform corrosion, while low-oxygen crevices beneath seals or backing bars promote localized attack (Belitz et al., 2016). Water chemistry ranges from soft, slightly acidic mountain runoff (pH ≈ 6, 20°C) to hard, saline estuarine water (pH ≈ 8, 35°C, 35 g L^{-1} Cl^{-}) (USGS, 2016). Turbulent eddies at gate lips drop local pressure below vapour pressure, generating cavitation micro-jets that superimpose mechanical damage on erosive particle impingement (Chahine et al., 2014). The combined action termed erosion–corrosion can remove 2-4 mm of steel in a single operational season, nullifying the nominal 2 mm corrosion allowance commonly adopted at the design stage (Schmitt et al., 2009).

Detailed Degradation Processes of Hydraulic Gates

Hydraulic gates are subjected to numerous harsh operating conditions that cause several related degradation processes. It is therefore important to understand the degradation mechanisms of hydraulic gates in order to improve their durability and reliability.

Abrasive-Erosive Wear and Synergistic Erosion

1. Abrasion of hydraulic gates is primarily caused by friction and impact from waterborne silt, sand and debris. Material loss rates depend on particle diameter, hardness, concentration, flow velocity and impact angle, as well as on the material's inherent hardness and microstructure (Zarrabi et al., 2020; Sun et al., 2023; Abdullayev et al., 2025).
2. Synergistic erosion of hydraulic gates occurs simultaneously with cavitation (the formation and collapse of vapor bubbles) and abrasive wear. Vapor bubbles formed by cavitation accelerate solid particles and increase their kinetic energy and hence their ability to erode the surface of the gate (Sun et al., 2023; Wang et al., 2024).
3. The synergistic erosion process increases the rate of material loss, vibrational frequency of the gate and likelihood of premature failure of flow components in the gate system (Sun et al., 2023; Wang et al., 2024).
4. Additionally, erosion-corrosion occurs at an increased rate in corrosive environments, whereby mechanical wear creates fresh metal surfaces that are readily attacked by chemicals, thereby enhancing both mechanical and chemical degradation of the gate (Wang et al., 2024).

Fatigue, Fretting and Crack Initiation

1. Fatigue wear is caused by cyclic loading of the gate and subsequent crack propagation within high stress areas of the gate (Yang et al., 2022; Mammadov, 2025).
2. Fretting of the gate occurs at interface contacts subjected to repeated small amplitude oscillations and promotes additional crack formation and initiation.
3. Combined pitting corrosion and fatigue: Corrosive environments produce pit formations that act as stress concentrators and thereby reduce fatigue life and promote accelerated crack growth (Yang et al., 2022; Chookah et al., 2011).

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Corrosion and Stress Corrosion Cracking (SCC)

1. General corrosion is the primary mechanism responsible for the corrosion of hydraulic gates. Steel gates are particularly vulnerable to general corrosion because they are continually submerged in water, alternately wet and dry, and are subject to biological corrosion (Dong et al., 2019).
2. Pitting and crevice corrosion: Localized corrosion causes the formation of deep pits in the gate, which can compromise the structural integrity of the gate and provide a site for crack initiation (Dong et al., 2019; Yang et al., 2022).
3. Stress corrosion cracking: Tensile stresses acting in conjunction with corrosive agents facilitate the formation and propagation of cracks in the gate. Common mechanisms of SCC include film rupture, hydrogen embrittlement and surface diffusion (Pedeferri, 2018; Hamdan et al., 2024).

Table 1. Key Degradation Mechanisms in Hydraulic Gates.

Mechanism	Description & Drivers	Impact on Gates	Citations
Abrasive–Erosive Wear	Sediment impact, cavitation, high-velocity flow	Surface loss, shape change	(Mammadov, 2025; Sun et al., 2023; Zarrabi et al., 2020; Abdullayev et al., 2025; Wang et al., 2024)
Fatigue & Fretting	Cyclic loads, micro-movements at contacts	Crack initiation, failure	(Mammadov, 2025; Yang et al., 2022; Chookah et al., 2011)
Corrosion (General/ Pitting)	Electrochemical attack, bio-corrosion, wet/dry cycles	Thinning, pit formation	(Yang et al., 2022; Dong et al., 2019)
Stress Corrosion Cracking	Synergy of stress and corrosive environment	Catastrophic cracking	(Hamdan et al., 2024; Pedeferri, 2018)

The degradation of hydraulic gate assemblies is primarily caused by a synergistic effect of several types of surface degradation, including abrasion, erosion, fretting fatigue, and various forms of corrosion. In addition to the inherent characteristics of each of these mechanisms, they can be affected by the physical and chemical characteristics of the material being used; the hydraulic flow regime in which it is operating and the environmental conditions under which it operates. Thus, to protect hydraulic gates from the effects of each of these degradation mechanisms and to monitor their degradation, an integrated approach to protection and monitoring should be adopted.

Types of Extreme Environments and Their Problems

Many times, the environment in which an engineering component operates exceeds the limitations of the mechanical and/or ceramic material(s) of construction. The four primary extreme environments high temperature, corrosive chemicals, high pressure/abrasion, and cryogenic/space vacuum, are characterized by both mechanical and thermal loads on metals and ceramic materials, as well as both chemical and electrochemical loads, thereby causing rapid degradation and necessitating design and application of purpose-built protective systems (Chhowalla, and Amaratunga, 2000).

High-Temperature Environments

Alloys in gas turbine engine combustor sections, gas turbine engine blades, and hypersonic leading-edge structures are exposed to temperatures up to 1000°C, in either oxidizing or sulfiding environments. The primary degradation mechanisms associated with exposure to high temperatures are oxidation, sulfidation, thermal fatigue, and high velocity erosive wear (Zhang et al., 2023). For example, aluminum oxide, chromium oxide, and titanium oxide have been found to form protective barriers against further oxidation of metal substrates (Zhang et al., 2023). Carbide- and boride-based coatings (e.g., WC, TiC, CrB, TiB_2) have been shown to exhibit superior wear resistance and corrosion resistance in high temperature, abrasive environments (Zhang et al., 2023). To improve the durability of coated surfaces, surface engineering techniques such as thermal spraying, plasma nitriding, water jet peening (WJP), and multifunctional cavitation (MFC) may be employed to enhance the bonding between the coating and substrate, as well as increase the mechanical strength of the coating (Zhou et al., 2022). As an example, WJP has been shown to improve the corrosion resistance of Cr-Mo steel at 500°C through the formation of dense oxide layers and beneficial residual stresses (Zhou et al., 2022). Additionally, nickel-aluminum alloy coatings have been demonstrated to maintain structural integrity at temperatures approaching 650°C, through the formation of a barrier layer consisting of a dense α-Al_2O_3 layer exhibiting low cation diffusivity (Wang et al., 2020).

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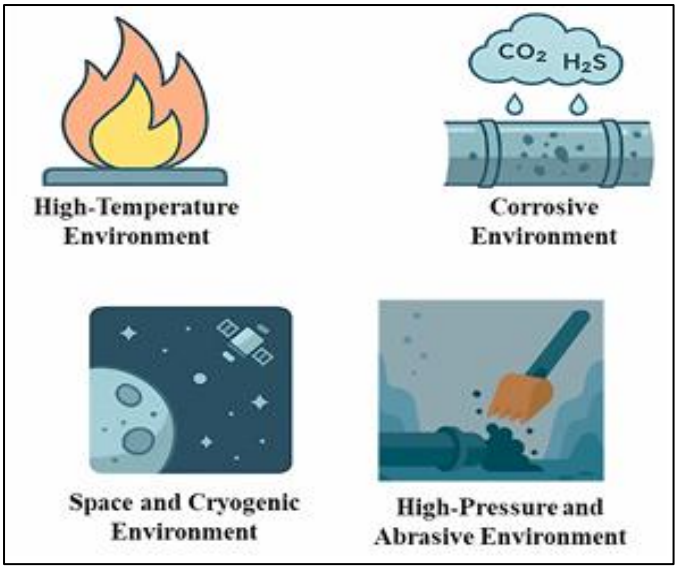

Figure 4. Overview of key extreme environments: high temperature, corrosive chemicals, cryogenic/space conditions, and high pressure and abrasion, which pose challenges to material performance.

Corrosive Chemical Environments

Chemical plants, oil/gas operations and marine construction expose metals to CO_2, H_2S, acids and Cl^-. Tribocorrosion (the synergistic effect between sliding or particle impingement and localized attack, Wood & Lu, 2024) commonly occurs at these locations, which may also be subject to localized attack (e.g., pitting, crevice, stress-corrosion cracking). FBE and TSA coatings have been widely used due to their high corrosion and mechanical durability (Hong et al., 2018). However, nanostructured or ultrafine-grained coatings may experience accelerated corrosion due to increased diffusivity along grain boundaries (Hussain et al., 2021). Controlled heat treatments after spraying help to promote grain growth and stress relief, thereby reducing localized corrosion susceptibility (Hussain et al., 2021). Dense, adherent layers produced from PEO or carbide-containing thermal spray coatings help to lengthen the operational time of components (Hussain et al., 2021).

High Pressure/Abrasive Environments

Subterranean drilling and mineral processing and deep-sea mining occur in environments characterized by high hydrostatic pressures and mechanical abrasion, as well as fluctuating loads that cause rapid wear and corrosion (Aribo et al., 2013). In addition to mechanical damage, alternating wetting/drying conditions in the "splash zone" enhance oxygen-cell corrosion (Aribo et al., 2013). In order to resist erosion and impact wear, sacrificial anodes and hard-facing or ceramic coatings have been used. Q235 mild steel exposed to deep-sea conditions demonstrate the significant impact of galvanic corrosion, thus illustrating the need for advanced coating technologies (Aribo et al., 2013).

Space/Cryogenic Environments

In space, equipment experiences severe thermal cycling (from 200°C to –200°C), extreme vacuum, intense radiation and cryogenic temperatures (Thielsch, 2001). Thermal cycling may result in expansion/contraction that can lead to micro-cracking and delamination (Thielsch, 2001), whereas long-term thermal loading can exceed material melting points (Thielsch, 2001). Materials currently being developed for coatings in this environment include hexagonal boron nitride (HBN), diamond-like carbon (DLC) and MoS_2. These materials functionally endure extreme temperatures, prevent cold-welding in vacuum and decrease wear when subjected to sliding contact (Thielsch, 2001). Tests simulating lunar regolith indicated that applying 2 μm DLC to 440C stainless steel reduced its abrasive wear rate by 90% compared with uncoated pairs (Thielsch, 2001).

High Performance Protective Coatings

Due to higher efficiency, longer service intervals and harsher operation conditions in aerospace, nuclear, deep sea and energy industries, protective coatings have become a fundamental aspect of component design. Four families of materials — ceramics, metallic alloys, composite polymers and nano/multilayer systems — now represent the majority of the market, each offering a unique combination of thermal, chemical and mechanical performance.

Ceramic Based Coatings

High-Temperature Ceramics (HTCs), such as ZrB_2-HfC-SiC (melting point 3000–4200°C), have provided oxidation protection for hypersonic leading edges and rocket nozzles (Wyatt et al., 2023). High Entropy Ceramics (HECs) with multication fluorite or disilicate lattices have extended thermal compatibility with SiC electronics up to 1600°C while allowing tunable optical and dielectric properties (Ward et al., 2024). Thermal Barrier Coatings (TBCs) made from YSZ, gadolinium zirconate or rare-earth silicates protect metallic substrates in gas turbines operating at temperatures above 1500°C, lowering the substrate metal temperature by 100–300°C and increasing the compression ratio (Grilli et al., 2025). Brittle nature of ceramics and low fracture toughness limit application and require strain tolerant microstructures (porous, columnar, segmented) and flexible bond coats.

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Metallic and Alloy Coatings

Where impact strength and thermal shock resistance are important, metallic overlays are preferable. Refractory High Entropy Alloys (RHEAs) of the HfNbTaZr and MoNbTaVW families will remain at yield strength greater than 500 MPa at 1200°C and will have low neutron capture cross sections for future generation fission and fusion reactors (Dixit et al., 2024). Air plasma sprayed Co-based Superalloy (L605) coatings have shown good corrosion resistance in hot corrosive environments containing sodium sulfate and vanadate found in industrial gas turbine applications (Kadivar et al., 2021). Wire arc sprayed Ni-20Cr coatings have achieved 900°C oxidation lifetimes over 5000 hours in molten salt solar heat exchangers at approximately 1/3 the cost of laser cladding (Kumar et al., 2024). A primary drawback is the weight increase caused by the coating's increased density; therefore, the optimal thickness is determined by the minimum required to block oxygen ingress.

Table 2. Summary of selected metallic/ceramic coatings for extreme conditions (data from Coatings).

Coating Type	Temperature Rating	Corrosion Resistance/Key Benefit	Reference
Ni-20Cr	900°C	High resistance in molten salt environments	Kumar et al., 2024
RHEAs	>1200°C	Strong mechanical properties; variants for radiation or corrosive use	Dixit et al., 2024
TBCs	~1300°C	Prevent oxygen ingress; ideal for aerospace engine applications	Grilli et al., 2025
Self-Healing Coatings	~1200°C	Maintain integrity and corrosion resistance over long service durations	Kadivar et al., 2021

Polymer and Composite Coating Systems

Polymer films such as Kapton (polyimide), PTFE, PEEK and polybenzimidazole are high-performance polymer films that maintain dielectric strength and radiation resistance across a temperature range from -150°C to +250°C. These materials are utilized on the majority of satellite bus panels and cryogenic feed line applications (Kadivar et al., 2021). In addition, waterborne epoxy coatings containing zinc-aluminate or graphene oxide are VOC compliant corrosion coating solutions for chemical plant splash zone applications (Sun et al., 2024). Although fiber reinforced composite materials (carbon / PEEK, glass / epoxy) have a lower mass then many other materials, they also have a high specific stiffness. However, UV induced surface chalking and moisture absorption may be detrimental to their lifespan. Therefore, there has been an increase in applying UV blocking clear coat or ceramic topcoat to many of these fibers reinforced composite materials.

Nanostructured and Multi-Layered Coating Systems

Nanostructured or multi-layered coatings can have properties altered by refining the material's grain size to less than 100 nm or by depositing alternating nano-layers (<50 nm period), while still maintaining the same bulk chemistry of the original material. A thin layer of nanocrystalline Ni or TiO_2 / Al_2O_3 deposited onto a substrate will produce a very dense and self-healing passive layer that reduces pit propagation rates in marine splash zones by 60% (Liu et al., 2024). Additionally, TiAlN / CrAlN nano multilayers have a hardness greater than 35 GPa and an oxidation onset at temperatures above 1100°C, which increases the lifespan of rocket turbo pump bearings by 3 times that of a monolithic TiAlN bearing (Liu et al., 2024). Surface nanopatterning (riblets, saw tooth) can alter how cavitation bubbles collapse and can decrease the amount of energy required to initiate cavitation by 25%, thereby delaying the formation of micro pits on ship propellers (Kadivar et al., 2021). However, these types of coatings require higher deposition costs and are sensitive to processing conditions, so they are typically used in the most critical applications.

Table 3. Typical properties of ceramic-based and metallic/alloy coatings.

Coating Type	Hardness (GPa)	Thermal Stability (°C)	Corrosion/ Oxidation Resistance	Advantages	Reference
Ultra-High-Temperature Ceramics	20–30	3000–4200	Excellent	Extremely high melting points, oxidation resistance at ultra-	Wyatt et al., 2023

				high temps	
High-Entropy Ceramics	15–25	>1600	Excellent	Tunable properties, compatibility with SiC electronics	Ward et al., 2024
Thermal Barrier Coatings	10–15	~1500	Good	Thermal insulation, reduced thermal conductivity	Grilli et al., 2025
Superalloy Coatings	5–10	~1100–1200	Very Good	High creep strength, good aerospace performance	Kadivar et al., 2021
Refractory High-Entropy Alloys	12–18	>1200	Very Good to Excellent	High strength at elevated temperatures, radiation resistance	Dixit et al., 2024
Ni-Based Alloy Coatings	6–10	~1000–1100	Good	Strong adhesion, cost-effective, suitable for boiler tubes	Kumar et al., 2024

Selection Strategy

The common service envelopes for each of the four classes of coatings are shown in Figure 3. Ceramic materials provide insulation at temperatures above 1000°C. Metals/alloys provide a good combination of toughness and strength at 500-1000°C. Polymer materials are suitable for use at temperatures below 250°C due to their chemical inertness and low mass. Nano-/Multilayer structures are selected to achieve maximum wear or corrosion fatigue life regardless of cost. Hybrid architectures (Ceramic Top Coat/Metallic Bond Coat/Polymer Sealant) are increasingly being used to leverage the synergistic effects of the various protective mechanisms.

Wear and Corrosion Mechanisms in Coatings

Adhesive and Abrasive Wear

Adhesive wear occurs through the close proximity of surfaces and results in the transfer of material from one surface to another. Abrasion causes damage to a surface through the motion of hard particulates over it. The balance between adhesive and abrasive wear in polyimide composites and carbon fiber reinforced polymers (CFRP's) is quite sensitive. Thermosetting and thermoplastics have excellent adhesive-wear properties against smooth metal substrates. However, the addition of graphite or PTFE filler to thermosets and thermoplastics may increase or decrease adhesive-wear properties, depending on the matrix material (Zhang et al., 2023). The abrasive-wear rate is directly proportional to the applied load and particle size until the point where fibers and matrix material begin to fail (Zhang et al., 2023). Factors within the environment also affect the wear rate; ultraviolet-A (UV-A) radiation, moisture and thermal shock all contribute to the acceleration of surface degradation. Although some micro-cracks may occur during this process, they are typically beneficial to relieving residual stresses (Wang et al., 2024). Therefore, it is important to formulate coatings according to the dominant type of wear anticipated in service conditions.

Oxidation and Hot Corrosion

At about 800°C chromium oxide (Cr_2O_3) provides short term protection by forming a scale, however water vapor transforms Cr_2O_3 into volatile $CrO_2(OH)_2$ and rapidly depletes the alloy in chromium. Therefore, alloys that form alpha-aluminum oxide (α-Al_2O_3) are generally preferred (Li et al., 2024). Molten salt fluxes such as Na_2SO_4-V_2O_5 spall these aluminum oxide scales; therefore, Cr and Al must be added to the alloy along with a protective overlay (aluminide, MCrAlY) to maintain a barrier that limits diffusion (Grilli et al., 2025). To accommodate thermal cycling, columnar or segmented ceramic top-coats that will tolerate strain should be used (Grilli et al., 2025).

Stress Corrosion Cracking and Pitting

Chloride ions disrupt passive film formation, creating local breakdowns and subsequent pit formation. These pits then act as stress concentrators, initiating stress corrosion cracking (SCC) when subjected to applied or residual tensile stresses (Jones et al., 1996). Splash zones of marine vessels and under-insulated areas are prime locations for accelerated pit nucleation due to

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environmental cycling of humidity and temperature (Belitz et al., 2016). Long-term field data based predictive models, along with non-destructive inspection techniques (ultrasound, radiography), are currently being employed to predict when maintenance and replacement of susceptible alloys are necessary using higher Mo or N content stainless steel alloys (Sridhar et al., 2020).

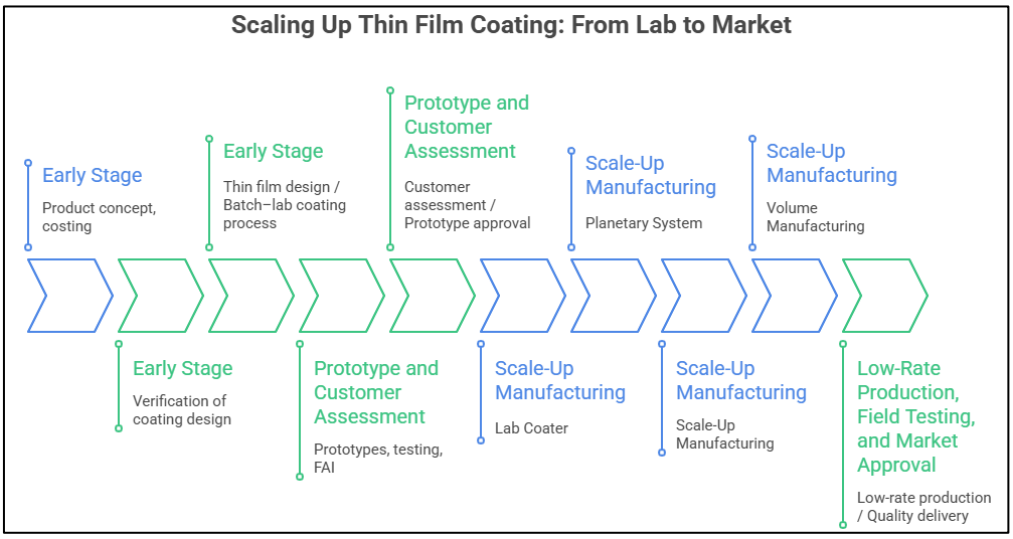

Figure 5. Scaling up thin-film batch-coating design to roll-to-roll processing for high-volume manufacturing.

Tribocorrosion: Synergistic Wear and Corrosion

Synergetic Effects of Mechanical Rubbing and Electrochemical Attack

For passive metals (Al, Stainless Steels, Ti) both mechanical rubbing and electrochemical corrosion simultaneously occurring on the same surface result in the removal of the protective oxide layer, thus resulting in increased corrosion and wear rates (Wood & Lu, 2024). Fretting in 3.5wt% NaCl (AA7075-T6) and in chloride rich body fluids (Hip Implants) demonstrate that an increase in load or sliding velocity will exponentially increase mass loss rates (Zhang et al., 2023; Masahashi et al., 2023). Therefore, integrated solution approaches such as the application of hard yet corrosion resistant coatings, controlled atmospheres and/or cathodic protection are essential in many industrial applications including petroleum, marine and biomedical (Wood & Lu, 2024).

Problems and Limitations

Scaling and Economic Viability of Coating Processes

Aspects of technical performance will be paramount in selecting protective coatings for a particular application; however, scaling and economic viability will also be essential to the successful implementation of these technologies into industrial settings. Among the physical-vapor deposition (PVD) coating processes studied, both magnetron sputtering and high-power pulsed magnetron sputtering (HPPMS) produce very consistent, uniform coatings that exhibit excellent adhesive properties and can be precisely engineered to achieve desired mechanical properties (Zhang et al., 2023). While both of these coating processes have limitations when attempting to scale to coat larger or geometrically complex parts, such as the housing of turbines or the structure of aerospace vehicles due to the requirement for vacuum chambers, substrate heating, and the need to maintain a specific deposition atmosphere (Zhang et al., 2023), the high initial investment required for vacuum systems along with the energy intensive nature of both the operation and maintenance of these systems place PVD in the realm of high value-low volume applications (Zhang et al., 2023).

Chemical vapor deposition (CVD), including low-pressure CVD (LPCVD) and plasma-enhanced chemical vapor deposition (PECVD), has advantages over PVD regarding scalability and has been successfully used in a wide variety of industries, including semiconductor, aerospace and automotive manufacturing (Wang et al., 2024). CVD can effectively coat complex-geometry substrates with highly conformal, ultra-pure thin films. However, the high-temperature reaction requirements and complexities associated with managing precursors, along with the need to perform this process under vacuum, result in increased costs and process sophistication, which place high-value applications as the primary justification for adopting CVD from an economic standpoint (Wang et al., 2024).

Thermal spray processes such as air-plasma spraying (APS) and solution-precursor plasma spraying (SPPS) provide the most scalable and highest throughputs of all the thermal spray processes (Hong et al., 2018). Thermal-spray processes can coat large areas and accommodate

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various geometries while operating at atmospheric pressure. As with many of the other thermal spray processes, the equipment investment may be substantial, but the relatively low operating costs of thermal spray processes, along with the ability to utilize relatively inexpensive feedstock materials, make them ideal for high-volume applications in a number of industries, including power generation, automotive, aerospace, and civil infrastructure (Hong et al., 2018). SPPS is particularly desirable because it enables the production of high-performance nanostructured coatings at relatively moderate cost (Hong et al., 2018).

Long-Term Durability and Maintenance

In addition to cost, long-term durability and maintenance requirements significantly impact the adoption of coatings in extreme environments. The results indicate that both the CrN and Cr(NO)PVD coatings on M50 tool steel and 304 stainless steel exhibit excellent high-temperature wear and oxidation resistance and low friction coefficients making them suitable for fast moving and thermally stressed components (Li et al., 2024).

Thermal sprayed cermet and ceramic coatings are still essential for surfaces subjected to abrasive and erosive wear such as turbine blades, boiler tubes, and control valves. The combinations of WC, Cr_3C_2, Al_2O_3 and ZrO_2 used in the cermet coatings exhibit sufficient thermal and mechanical stability at severe operating conditions; additionally, further improvements in the coatings' durability can be achieved by applying post deposition laser sealing or densification to minimize porosity and prolong time until cracking occurs (Grilli et al., 2025).

Arc-sprayed Fe-based amorphous and nanocrystalline coatings exhibit extremely good cavitation-erosion properties when applied in hydraulic machinery due to the combined high hardness and elasticity of the coatings (Masahashi et al., 2023). The fine nanostructures promote the resistance against local fatigue while simultaneously preventing brittle fracture; optimal surface roughness (Ra = 0.5 – 1 µm) will also positively affect the performance of the coatings (Masahashi et al., 2023).

To increase the service lifetime of coatings, several approaches are available:

1. Recoatable coating systems (e.g., HVOF, arc spraying) allow for the removal of coatings during maintenance work and subsequent recoating thereby reducing the maintenance downtime by 50 %.
2. Sacrificial wear layers protect inner functional layers in multi-layer architectures, thereby increasing the service life of the total system by 30–40 %.
3. In addition to these traditional approaches, new smart coatings are currently being developed which adapt to changing environmental conditions e.g., by self-lubricating or hardening when stressed. This enables a reduction in the need for maintenance activities.

Environmental and Regulatory Considerations

Climate-dependent factors such as humidity, saltwater exposure, temperature cycles and gaseous pollutants (SOx, NOx) accelerate corrosion and wear processes and thus contribute to worldwide estimated annual corrosion-related losses of over $1.8 trillion (Koch et al., 2002). Utilization of best-practice corrosion protection measures could reduce this loss by up to 25-30% (Koch et al., 2002).

Major policy and regulatory trends in Europe and North America, including climate and energy policies and regulations, are driving the innovation process in the area of protective coatings:

a) REACH and Cr (VI) substitution: The phase out of hexavalent chromium has stimulated research into environmentally friendly substitutes, including Cr (III), Zr-based chemistries, tartaric/sulfuric anodizing and silane-based primers, although the long-term durability of these alternatives still requires validation (Jones et al., 2020).
b) Green chemistry in energy sectors: New products such as biodegradable inhibitors, polymer-based linings and fibre reinforced composites are being developed to replace conventional steel systems containing hazardous substances (Wood & Lu, 2024).
c) Recycling driven alloy design: Post-consumer aluminum scrap contains trace amounts of elements that can impair corrosion performance and thus motivate the development of alloys and coatings that can tolerate impurities (Sridhar et al., 2020).
d) International standards: ISO TC 265 establishes limits for impurities in CO_2 transport pipeline materials; qualification of MCrAlY and epoxy phenolic lined coatings for 100bar, 50°C dense phase CO_2 is underway (Belitz et al., 2016).

Future Directions

Development of Sustainable Coating Materials

The world's demand for synthetic polymers is predicted to rise by nearly threefold to approximately 1.2 Gt by 2060 (Zhang et al., 2023). Therefore, the transition towards bio-based alternatives will become even more urgent. Bio-based core-shell pigments (TiO_2-coated talc) have already demonstrated enhanced optical and antibacterial properties with reduced TiO_2 usage in paper coatings (Liu et al., 2024). Chitosan derived from

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seafood-shell waste provides inherent antimicrobial activity and acceptable oxygen barriers, however, it shows high sensitivity to water and poor adhesion to hydrophobic metals; thus, treatment options such as grafting or cross-linking are required to stabilize the chitosan (Wang et al., 2024). Mechanically robust, biodegradable films can be produced using nanocellulose and cellulose acetate, yet swelling in humid environments is currently the main limiting factor for application in marine or outdoor environments (Sun et al., 2024). In the frame of circular economy feedstock alternatives made from agricultural residues, crustacean shells, or recycled paper fibers are being formulated into water-borne dispersions that can be applied by spray or dipping thereby closing the material loops and reducing the demand for petrochemicals by > 40 % (Sun et al., 2024). Figure 10 schematically illustrates the renewable resources and the resulting bio-polymer classes.

Investigation of Coatings for New Application Areas

Space environment: In the extreme vacuum (10^-6 Pa), high temperatures (-150°C - +200°C), UV/VUV radiation and proton irradiation, ultra-low out-gassing, radiation stable systems are demanded. Diamond like carbon (DLC), MoS_2 and hexagonal BN films prevent cold welding and retain $\mu < 0.1$ in vacuum (Chhowalla, and Amaratunga, 2000). Multilayered Al_2O_3/SiO_2 stacks protect space laser optics from electron-induced defect absorption and provide resistance to atomic oxygen erosion (Thielsch, 2001). Micrometeoroid shield concepts combining 100 µm Kevlar / epoxy above DLC-coated Al panels double the ballistic limit velocity of meteoroids without adding weight (Thielsch, 2001).

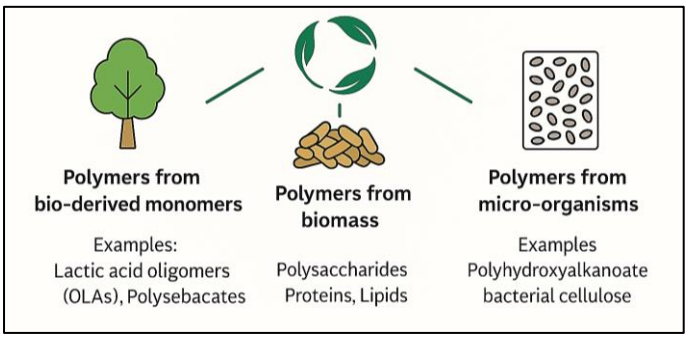

Figure 6. A conceptual map of renewable sources for biopolymer-based coating materials.

1. An economy based on hydrogen is currently threatened by the hydrogen diffusion and embrittlement which may occur within steel pipelines and hydrogen storage vessels. Layers of ceramic (SiC, Al2O3) or multilayered Ni-TiN, less than 5 microns in thickness, reduce hydrogen permeability to greater than 10^4 at 350 C, while also allowing the layer to remain ductile during repeated pressure cycles (Hong et al., 2018). Amorphous Fe-Cr-P-B layers can be cold-sprayed onto existing in-service piping to create a repairable, weld-compatible barrier (Hong et al., 2018).
2. Coatings produced using additive manufacturing: Cold spray and directed-energy deposition techniques have been developed to deposit site-specific gradients of materials such as WC-Co cermets or Ni-Cr-Al compositions on worn impellers, thereby reducing material waste by 80% relative to oversize cladding (Zhang et al., 2023). Laser alloying of 1–2 weight % Si into arc-sprayed Fe coatings produces refined nanostructures and increases the life of these coatings against cavitation erosion by 3 times without adding feedstock (Zhang et al., 2023).
3. Smart & multifunctional surfaces: Microcapsules containing corrosion inhibitors that release when the pH falls below 6 are being incorporated into thermal-spray polymer/ceramic hybrids for the protective coatings on offshore wind monopoles (Sun et al., 2024). Gradient PEEK-TiN coatings that contain both electrical conductivity and antibacterial properties, used in flexible electronic devices and biomedical implants, were deposited using a combination of fused-filament fabrication and reactive sputtering (Sun et al., 2024).

Conclusion

Hydraulic gates are vital to water security globally, but their operating lifetimes are regularly reduced due to the combined effects of abrasively erosive sediment, cyclically applied mechanical loads and chemically aggressive water. It has been demonstrated in this review that traditional corrosion allowances and paint systems are insufficient to extend the maintenance-free life of hydraulic gates, instead, high velocity oxy fuel cermet coatings increase the life of the gates significantly (several fold) under field-relevant conditions of erosion-corrosion. Additionally, post-spray fusion or laser seal processing decreases porosity to less than 1% and increases adhesion strength to greater than 70 MPa, thus preventing both through-thickness cracking and galvanic attack. Therefore, the current life prediction models must include real sediment spectra, climate-driven wet/dry cycling and biofilm chemistry to transition from qualitative to quantitative risk assessments.

In the future, the development of the next generation of gate coatings will be determined by the convergence of three trends:

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1. Sustainable feedstocks chitosan- or nanocellulose reinforced primers made from seafood or agricultural waste reduce petroleum chemical demand while maintaining barrier function;
2. Smart coatings that report damage in real time, embedded micro-capsules that release inhibitors at low pH or color-changing pigments that indicate coating failure prior to substrate corrosion begin;
3. Additive manufacturing enabled repairs cold-spray or directed-energy deposition enables in-situ buildup of gradient cermets on eroded gate edges, reducing material waste compared to oversize cladding.

Therefore, the integration of cermet overlays with real-time corrosion monitoring, bio-based primers, and robotic re-spray capabilities enables water resource managers to transition from reactive maintenance to predictive, low-carbon asset management. The next decade will most likely witness the first field deployment of hydrogen-tight, radiation-resistant, and self-healing coatings on large-scale hydraulic infrastructure to ensure that gates protect water, energy, and food security in a warmer world.

Conflict of interest

None

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